Estimation of fracture energy of large earthquakes based on heterogeneous stress drops and fault rupture velocities

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Fracture energy is a fundamental physical property of earthquakes governing its nucleation, rupture growth and arrest. The most widely used approach to estimate fracture energy (G) is based on the energy budget during an earthquake, where fracture energy is obtained by subtracting the energy radiated by seismic waves from the available potential energy change during fault rupture (usually referred to G', or "seismological" fracture energy). To make this problem tractable using the seismological approach, several simplifications have to be assumed such as the use of simple averages for displacement and stress on the fault plane as well as the assumption of a simple relation between fault shear stress and slip (i.e. slip weakening friction law). However it is well known that slip and stress across the fault plane (namely fault rupture process) can be highly variable and complex for large earthquakes.

To estimate fracture energy in this study we use the LEFM (Linear elastic fracture mechanics) approach and assume that heterogeneous fault rupture can be approximately described as the superposition of anti-plane and in-plane fault rupture modes. We calculate local fracture energy across the fault plane as the product of a 'static' stress intensity factor K* (proportional to local stress drop and the square root of crack length) and a function of local fault rupture velocity at the rupture front. Total fracture energy is obtained as the integral of local fracture energy over the entire fault surface.

We estimated fracture energy (G) of 173 earthquakes worldwide (moment magnitudes larger than 7.0) using the extensive database of slip models compiled by the National Earthquake Information Center of USGS. We first calculate the stress drop distributions, as well as local rupture velocity distributions (Pulido and Dalguer, 2009) using the slip models and sub-faults rupture times available in the database. Our results show highly heterogeneous distribution of stress drops and local fault rupture velocities. Fault rupture across the fault largely takes place in the sub-shear domain for most of the earthquakes considered in this study, although it can typically become super-shear at local patches within the fault. For this study we calculated fracture energy only for ruptures in the sub-shear domain. Super-shear rupture contribution to fracture energy is a subject for a future study. Our results indicate a strong fault weakening with increasing slip (decrease in G) for large earthquakes (M>7), where G is approximately proportional to the average fault slip. This weakening of G is significantly larger than the one reported for small earthquakes (where G is proportional to the square of slip). Our results also show that G' systematically underestimates fracture energy for large earthquakes.

Keywords: Source process of earthquakes, Fracture energy, Fault rupture velocity, Stress drop